PROCEEDINGS OF SCIENCE

New Physics Results from the FASER Experiment

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FASER, the ForwArd Search ExpeRiment, has successfully taken data at the LHC since the start of Run 3 in 2022. From its unique location along the beam collision axis 480 m from the ATLAS interaction point, FASER has world-leading sensitivity to many models of long-lived particles. In this talk, a brief status update of the FASER experiment will be given, followed by a summary of the results of a search for a light, long-lived particle decaying into a pair of photons. In particular, axion-like particles (ALPs) are targeted where the ALP couples to the electroweak gauge bosons. The search uses LHC Run 3 data collected at $\sqrt{s} = 13.6$ TeV corresponding to an integrated luminosity of 57.7 fb^{-1} to place new constraints on ALP parameter space for masses up to 300 MeV and coupling strengths as low as $g_{aWW} \sim 10^{-4}$ GeV^{-1}. The results are also interpreted in the context of other new physics signatures with multiple photons in the final state.

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1. The FASER detector

FASER, the ForwArd Search ExpeRiment [1, 2], is a relatively new detector designed to search for new light and weakly-interacting long-lived particles (LLPs) produced in collisions at the LHC. The detector is ~ 7 m long with an active transverse area given by a circle of radius 10 cm [2]. It is located in the unused TI12 service tunnel, 480 m away from the ATLAS [3] interaction point (IP1) along the collision axis. Charged particles originating from IP1 are deflected by the LHC magnets, whilst an additional shielding of 100 m of rock and concrete between the LHC beampipe and the FASER detector helps to further reduce potential backgrounds.

1.1 FASER design

A schematic of the FASER detector is shown in Figure 1. It consists of an emulsion detector for neutrino detection[1], a series of scintillator stations for triggering and rejection of events containing high energy muons, a tracking spectrometer, a two-layer preshower system, and a calorimeter for electromagnetic (EM) energy measurements. A 1.5 m long decay volume is immersed together with the tracking spectrometer in a 0.57 T dipole magnetic field [2].

1.2 FASER performance

Data-taking was continuous and largely automatic throughout Run 3. The trigger rate, dominated by signals from high energy muons in the scintillator and calorimeter systems, averaged around 1 kHz with a maximum of 2 kHz. An average deadtime of 1.3%, combined with a couple of system crashes, limited the recorded luminosity to 97.4% of the delivered value. A total integrated luminosity of 57.7 fb^{-1} is used for the analysis described in this note.

2. Axion-like particles at FASER

Axion-like particles (ALPs) are hypothesised gauge-singlet pseudoscalars that appear in many proposed extensions to the Standard Model (SM). The FASER detector is sensitive to a variety of ALP models [4], in particular models where the ALP a couples to the $SU(2)_L$ gauge bosons $W^{\mu\nu}$, as described by the Lagrangian [5–7]

$$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{1}{4} g_{aWW} a W^{a,\mu\nu} \tilde{W}^a_{\mu\nu} , \tag{1}$$

where m_a is the ALP mass, and g_{aWW} is the coupling strength. After electroweak symmetry breaking, the ALP acquires couplings to the weak bosons and photons. The main production mechanism for such ALPs is via FCNC decays of B-hadrons, and the dominant decay mode is to a pair of photons. FASER is expected to provide sensitivity in previously uncovered parameter space for masses $m_a \sim 60 – 400$ MeV and couplings $g_{aWW} \sim 10^{-5} – 10^{-3}$ GeV^{-1}.

[1] The emulsion detector is not directly used in the analysis presented in this note, but provides additional background suppression via its eight interaction lengths of tungsten.

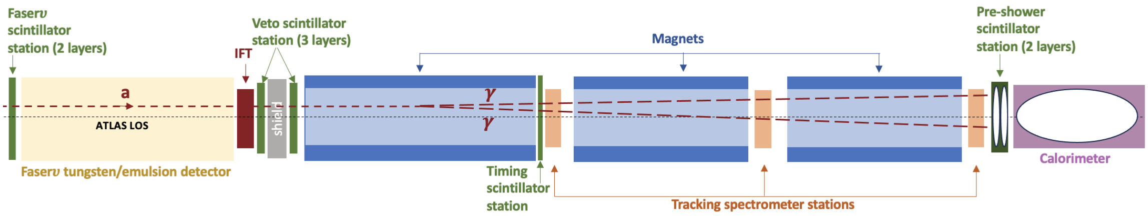


Figure 1: Schematic of the FASER detector showing the signature of an ALP. The white areas indicate where detector signals would be expected.

3. Search for axion-like particles at FASER

FASER searches for ALPs decaying to a pair of photons [8]. The experimental signature is a large calorimeter energy and minimal activity in the tracker and VetoNu, Veto and Timing scintillators. Data with no signal in the VetoNu and Veto scintillator stations and a calorimeter energy larger than 100 GeV were initially blinded during the optimisation of the analysis signal region selection.

3.1 Signal generation

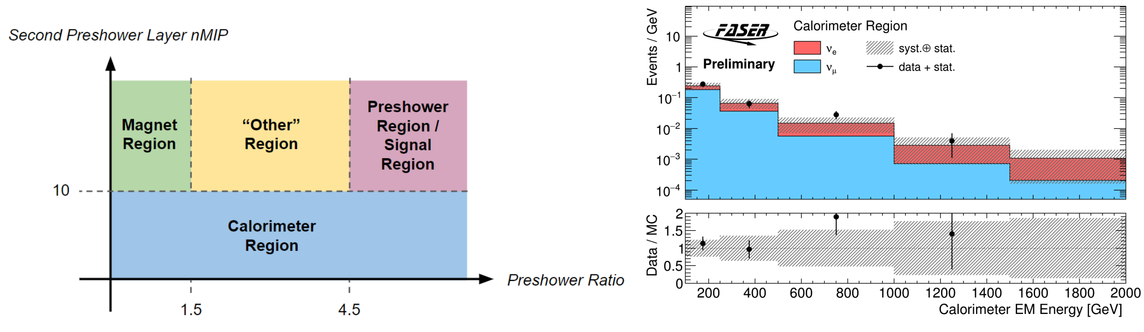
Signal events are generated using `FORESEE` [9] with `POWHEG+Pythia` [11] used to simulate forward B-hadron production, and `EPOS-LHC` [10] used to model the subdominant contribution from kaon decays. The uncertainties on the signal flux are around 60% depending on the ALP mass and coupling, and are estimated from scale variations in the case of B-hadron production, and by comparing the predictions from different generators for the kaon component. An additional 20% uncertainty is applied on the B-hadron branching ratio for decays to LLPs.

3.2 Event selection

Events are selected to maximise the potential for discovery. The event time is required to be consistent with a colliding bunch at IP1. Since ALPs and their decay photons are electrically neutral, the signal in the VetoNu, Veto and Timing scintillators is required to be no larger than half of that expected from a MIP. These requirements also effectively remove backgrounds from high energy muons. The charge deposited in the second layer of the preshower, and the ratio of the charges in the two layers, are both required to be consistent with an EM shower. Finally an energy larger than 1.5 TeV is required in the calorimeter. The efficiency of the selection for signal events decaying in the FASER fiducial volume varies between 5 – 80% depending on the ALP mass and coupling.

3.3 Backgrounds

The dominant background comes from electron and muon neutrinos interacting in the preshower layers and is found to be 0.42 ± 0.38 events. This is estimated using dedicated MC simulations [12] based on EPOS-LHC [10] and `POWHEG+Pythia` [11] for modelling the forward production of light and charm hadrons respectively, with `GENIE` [13, 14] used to simulate neutrino interactions. A flux uncertainty of around 80% is calculated based on generator comparisons and scale variations. The predictions are validated in two regions defined by selections on preshower variables where the



(a) **(b)**

Figure 2: **(a)** Schematic of the validation and signal regions. **(b)** Calorimeter EM energy distribution in the calorimeter region.

neutrinos are expected to interact predominantly in either the magnet or calorimeter. The region definitions are shown schematically in Figure 2a. Good agreement between the data and MC is found in the validation regions, as shown for example in the calorimeter region in Figure 2b.

Additional background contributions from scintillator inefficiencies, neutral hadrons, large-angle muons, cosmic rays, and beam debris were studied and found to be negligible.

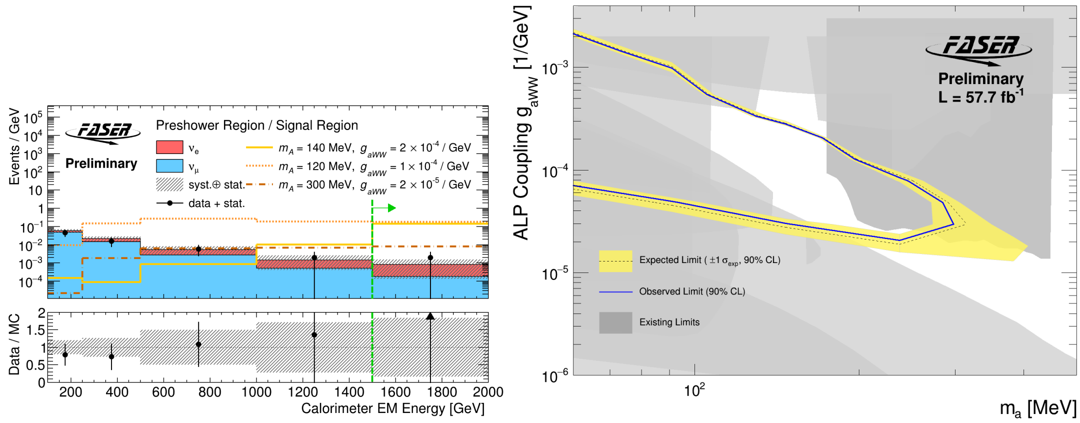
4. Results

A single event with a calorimeter energy of 1.6 TeV is observed in the signal region after unblinding, consistent with the background prediction. A comparison between the data and the neutrino MC prediction in the preshower region and signal region is shown in Figure 3a alongside a few representative ALP signal points. Since no significant excess is observed, 90% confidence level exclusion limits are instead set in the ALP parameter space according to the CLs prescription. The exclusion contours probe previously uncovered regions of parameter space, as shown in Figure 3b.

The data and background prediction in the signal region are also used to set limits on other new physics models involving multiple photons in the final state. These include ALPs coupling only to photons, ALPs coupling only to gluons, bosons arising from a $U(1)_B$ gauge symmetry, and a scalar coupling only to up-quarks. In all cases previously uncovered regions of the corresponding parameter spaces are excluded [15].

5. Conclusion

The FASER detector has continued to successfully take data throughout Run 3. The recorded data was used to provide constraints on previously unexplored regions of ALP parameter space, where the analysis was optimised for an ALP coupling to $SU(2)_L$ gauge bosons. ALP masses up to 300 MeV and couplings as low as $g_{aWW} \sim 10^{-4}$ GeV^{-1} are excluded. In addition, the results are interpreted in the context of other multi-photon signatures, where new parameter space is excluded for a range of new physics scenarios. These results add to the growing catalogue of searches for physics beyond the SM with FASER, following a previous search for dark photons [16].



(a) **(b)**

Figure 3: **(a)** Calorimeter EM energy distribution in the preshower region, with the signal region indicated by the green arrow. **(b)** Expected and observed exclusion limits.

Future analyses for multi-photon signatures are expected to benefit from the planned upgrade to the preshower system, which will provide a transverse granularity capable of resolving multiple photons [17]. In addition, a large scale upgrade to FASER is planned for the high-luminosity LHC (HL-LHC) as part of the Forward Physics Facility (FPF) [18], which is expected to provide a significant improvement in the sensitivity for such new physics searches.

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